Evaluation of CHAMP radio occultation refractivity using data assimilation office analyses and radiosondes

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[1] The radio occultation experiment on the CHAMP satellite has been collecting observations of the Earth's atmosphere since April 2001. Previous work has shown that diffraction effects not accounted for by geometrical optics processing can be partially corrected by back-propagation and canonical transform methods, such as implemented at the Jet Propulsion Laboratory. In the present paper we evaluate the bias and standard deviation of refractivity differences between Data Assimilation Office global analyses and observations processed by these three methods. In the tropics at 2–5 km altitude, the refractivity biases range between -2.5% and -0.5% for geometrical optics, between -1% and 0.5% for back-propagation, and between -0.5% and 1.5% for canonical transform. We also assess the methods by performing one-dimensional variational temperature retrievals and comparing them with close radiosondes. Our final conclusion is that canonical transform is a better candidate than geometrical optics and back-propagation for generating GPS radio occultation datasets for data assimilation. *INDEX TERMS:* 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 6904 Radio Science: Atmospheric propagation; 6969 Radio Science: Remote sensing; 6994 Radio Science: Instruments and techniques. **Citation:** Poli, P., C. O. Ao, M. de la Torre Juárez, J. Joiner, G. A. Hajj, and R. M. Hoff, Evaluation of CHAMP radio occultation refractivity using data assimilation office analyses and radiosondes, *Geophys. Res. Lett.*, *30*(15), 1800, doi:10.1029/2003GL017637, 2003.

1. Introduction

[2] The Global Positioning System Meteorology (GPS/MET) experiment (1995–1997) demonstrated the concept of observing the Earth's atmosphere by radio occultation (RO) of GPS signals [e.g., *Ware et al.*, 1996]. A GPS RO occurs when a GPS receiver placed on a low Earth orbit satellite sees one spacecraft of the GPS constellation either setting or rising behind the Earth's atmosphere. This technique collects measurements of extra time delay induced by the atmosphere on rays propagating between the transmitter and the receiver, from which atmospheric Doppler shift, bending angle and refractivity can be derived [*Kursinski et al.*, 1997].

[3] With the advent of GPS RO missions such as onboard the Challenging Minisatellite Payload (CHAMP), GPS ROs may soon reach a stage where the number of occultations collected per day becomes comparable with the current number of daily operational radiosondes (RS), and may potentially impact numerical weather prediction and/or climate monitoring. In this perspective, it is important that GPS RO processing methods be evaluated before operational use.

[4] The processing of GPS RO data usually assumes that wave propagation of the GPS signals in the Earth's atmosphere can be well approximated by a single ray leading to the geometrical optics (GO) refractivity profiles. However, since the wavelength of the GPS signals is not infinitely small as assumed in GO, diffraction effects spread the signals, thus degrading the vertical resolution [e.g., *Kursinski et al.*, 1997; *Gorbunov et al.*, 1996]. Furthermore, sharp refractive index gradients may split one ray into several carrying a significant fraction of the initial total power, before being recombined in the receiver. In such case, multi-path is said to occur. The corresponding measurement is then representative of a combination of several rays which have probed various parts of the atmosphere.

[5] After various analyses of GPS/MET data processed using GO [e.g., *Ware et al.*, 1996], more advanced approaches have been investigated [e.g., *Sokolovskiy*, 2001]. Essentially three methods have been developed: the sliding spectral method (also called radio-optical), the back-propagation (BP) method (also called diffraction correction) [*Gorbunov et al.*, 1996], and the canonical transform (CT) method [*Gorbunov*, 2002]. We focus in this paper on refractivity obtained from CHAMP *via* GO, BP, and CT processings at the Jet Propulsion Laboratory (JPL). We compare these three datasets with Data Assimilation Office (DAO) analyses. We also assess the quality of each dataset by deriving one-dimensional variational (1DVAR) temperature retrievals and comparing them with close RS.

2. JPL Refractivity Processing

[6] *Hajj et al.* [2002] have described in detail the processing of raw GPS RO measurements into refractivity assuming GO. The idea is that the signals are assumed to remain sufficiently focused so that one ray only (after time-averaging) needs to be considered to obtain the dependence of the bending angle versus the impact parameter (or asymptotic ray-miss distance). This method is an inadequate approximation if multi-path and/or super-refraction occur.

[7] In order to account for diffraction effects, *Marouf et al.* [1986] introduced the BP method to profile Saturn's rings using radio occultation measurements. The method was applied to the Earth's atmosphere by *Gorbunov et al.*

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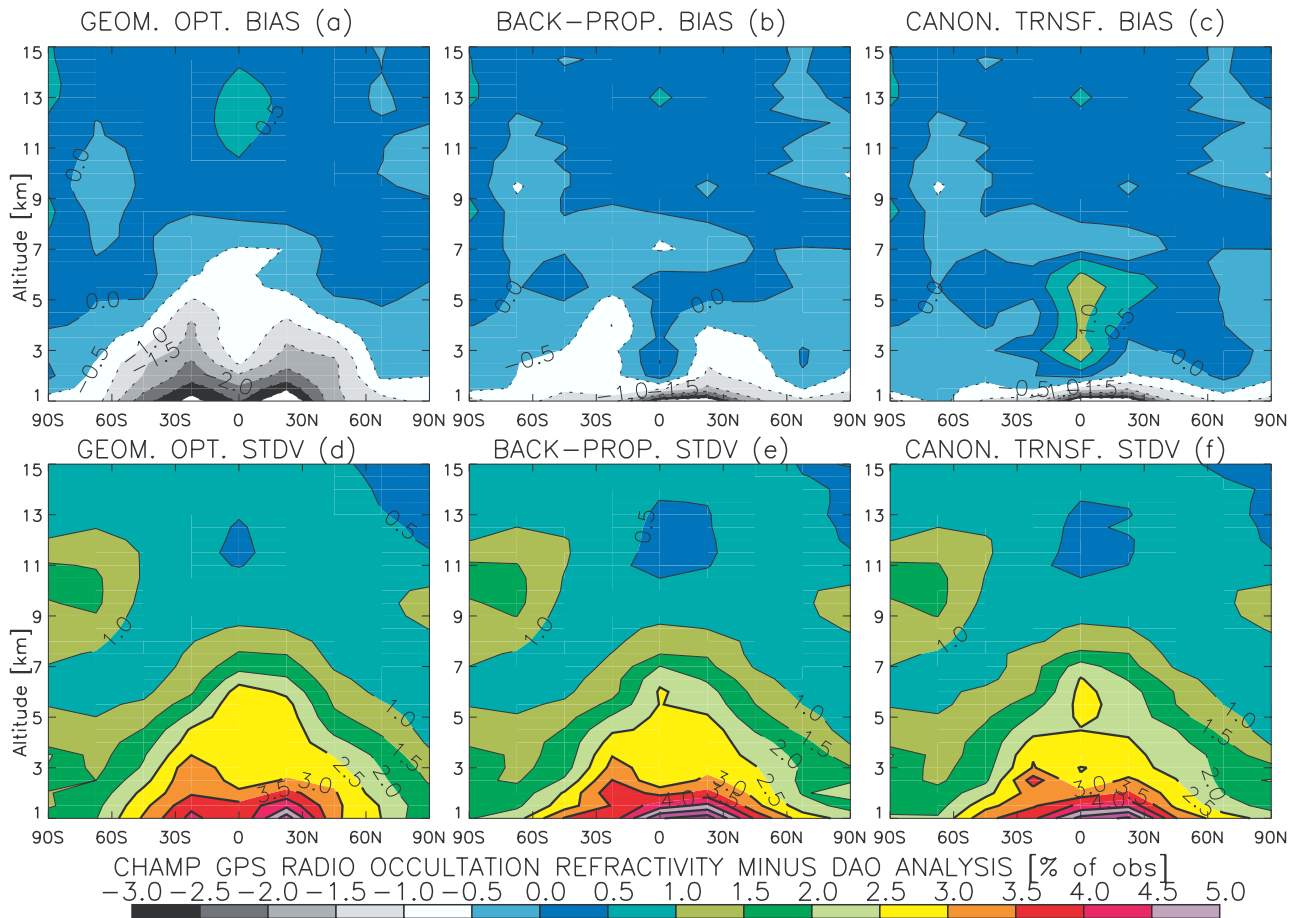
Figure 1. Refractivity differences CHAMP GO (BP and CT) minus DAO analyses in percent of GO (BP and CT, respectively). Bias shown in plot a (b and c, respectively), standard deviation in plot d (e and f, respectively).

[1996]. Using diffraction theory, the BP method reconstructs the atmospheric bending at a plane closer to the ray tangent points, where multipath effects present at the receiver are eliminated or at least mitigated. Later, it was shown that BP would not work perfectly under severe multipath conditions. This led to CT, a generalization of the BP method. CT can unravel all multipaths under the assumption of a spherically symmetric atmosphere [*Gorbunov*, 2002].

[8] Refractivity is derived from bending angles obtained by GO, BP, or CT, assuming spherical symmetry via an Abel transform [*Hajj et al.*, 2002]. The air refractivity N is a linear function of refractive index n, and can be related to atmospheric physical quantities *via*

$$N = 10^6(n - 1) = b_1 \frac{P}{T} + b_2 \frac{P_w}{T^2}, \qquad (1)$$

[*Smith and Weintraub*, 1953] (neglecting scattering and in a neutral atmosphere), where P is the total atmospheric pressure (dry air and water vapor) in hPa, T the temperature in K, P_w the partial pressure in water vapor in hPa, $b_1 = 77.6$ K $\cdot$ hPa^{-1}, and $b_2 = 3.73 \times 10^5$ K$^2 \cdot$ hPa^{-1}.

3. CHAMP Refractivity Observations

[9] Launched in July 2000, the German CHAMP mission managed by GeoForschungZentrum (GFZ) Potsdam carries

a second-generation 'Blackjack' JPL-built GPS receiver as part of a joint German/US GPS RO experiment [*Wickert et al.*, 2003]. In the present paper we use CHAMP refractivity data collected between May 14 and May 31, 2001. Because each processing method yields a slightly different dataset due to JPL quality control criteria (QC), we use the intersection of the three GO, BP, and CT datasets, i.e. 1881 GPS ROs, out of which 76% penetrated down to 1 km altitude or less. The JPL QC retains all occultations presenting retrieved differences as compared to National Centers for Environmental Prediction (NCEP) analyses smaller than 10K in temperature and smaller than 20% in refractivity (10% only for GO) everywhere between 0 and 30 km altitude. Investigations of which particular occultations failed the various QCs are currently underway to help improve the implementation of each processing method.

4. Comparison of Refractivity With DAO Analyses

[10] One method to assess the quality of GPS RO data is to compare these measurements with local refractivity derived via application of (1) to three-dimensional fields of temperature and humidity generated by a data assimilation system. We use global analyses from the DAO's next-generation finite volume Data Assimilation System (fvDAS, Data Assimilation Office Algorithm Theoretical Basis Doc-
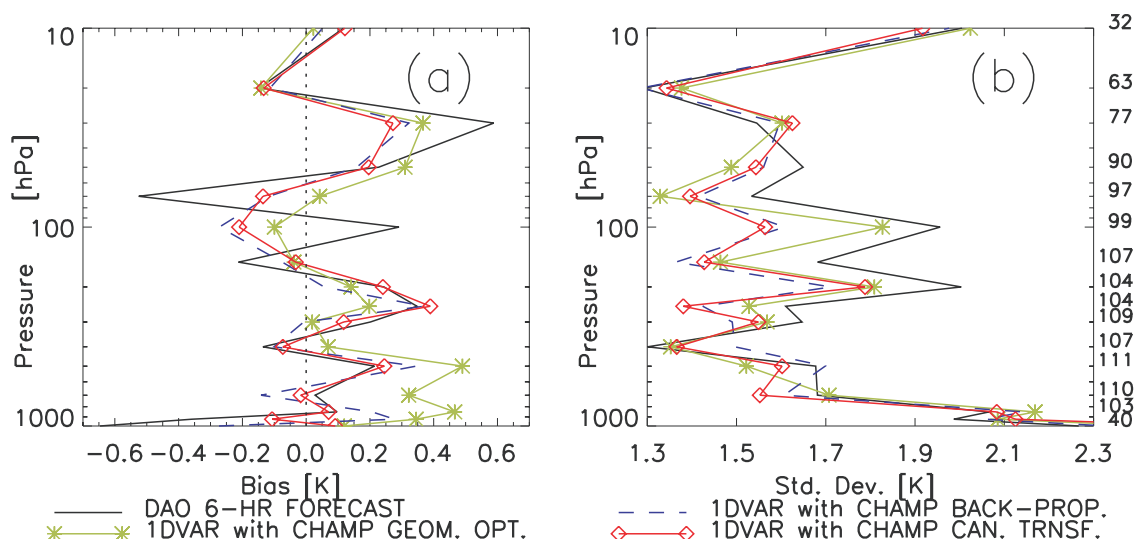
Figure 2. Comparison of 1DVAR temperature analyses made using CHAMP RO refractivity from various processing techniques with close radiosondes (RS).

ument (ATBD) version 2, *Draft*, available from the World Wide Web at http://polar.gsfc.nasa.gov/sci_research/ atbd_pages) as independent estimates of the state of the atmosphere. The fvDAS was run with 55 levels between the surface and 0.01 hPa and a horizontal resolution of 1×1.25 degrees (latitude/longitude). The observations assimilated in the analyses include conventional observations such as RS, cloud-track winds, interactive retrievals derived from (Advanced) TIROS Operational Vertical Sounder (A)TOVS, and Special Sensor Microwave Imager (SSM/I) total precipitable water.

5. Variational Temperature Retrievals

[11] We generate variational temperature profiles from CHAMP refractivity observations and compare them with close RS temperatures as a reference to assess the quality of refractivity obtained by GO/BP/CT processings. Our variational scheme is a 1DVAR analysis described in detail by *Poli et al.* [2002]. The 1DVAR analysis uses a priori information (fvDAS 6-hour forecasts), and estimates of refractivity errors and a *priori* errors expressed in the form of error covariance matrices. Close RS are defined as less than 280 km arc distance and within 1 hour of the CHAMP occultation event.

6. Results and Discussion

[12] We are first interested in the differences between GPS RO refractivity and that computed from DAO analyses, and more importantly their relative differences depending on the processing method. Since diffraction effects are more frequent in the lower atmosphere, we focus our comparison below 15 km altitude. Above 15 km altitude, we verified that the differences are very similar for each dataset. We average the refractivity differences for all the occultations contained in latitude bins between 90°N and 70°N, 70°N and 50°N, and so on. In the vertical axis, we interpolate all the refractivity profiles to a grid with 500 m altitude spacing. Since refractivity varies by about one order

of magnitude in the considered altitude range (0–15 km), we characterize the differences in terms of percent of observed refractivity (GO, BP, or CT).

[13] Figure 1a shows the mean of the refractivity differences for GO. Significant biases of about −3.5% to −1.5% can be observed below 3 km altitude in the tropical regions. This bias is consistent with a previous comparison made between GPS/MET refractivity and DAO forecasts [*Poli et al.*, 2002]. The so called 'refractivity bias' has been identified by other authors using different global analyses [e.g. *Kursinski and Hajj*, 2001]. The origin of this bias has been explained in detail by Ao et al. (Lower troposphere refractivity bias in GPS occultation retrievals, accepted for publication the *Journal of Geophysical Research*, doi:10.1029/2002JD003216, 2002). Before being resolved, this bias represented a problem for variational assimilation of GPS RO refractivity which assumes unbiased observations [*Poli et al.*, 2002] as well as for humidity retrievals [*Høeg et al.*, 2001]. The bias is smaller for higher latitude regions (between −1.5% and 0% beyond 60°N or 60°S) where the absolute amount of water in the atmosphere is smaller. Above 6 km altitude, the bias is in the range −1% to 0.5%.

[14] The BP refractivity bias shown in Figure 1b is significantly smaller than GO when compared with the DAO analyses. It is usually between −1.5% and 0.5% everywhere except in some very limited areas where more water vapor is present (North mid-latitude Spring at 1.5 km altitude). Differences between BP and GO are small for altitudes above 7 km, where diffraction effects are less important.

[15] The CT refractivity bias shows positive differences with respect to the BP refractivity bias: a small region of positive bias (0.5%–1.5%) now appears near the Equator between 2 and 6 km altitude.

[16] Another metric of interest is the standard deviation of the refractivity differences. Figure 1d shows that the GO standard deviations range from 3%–5% below 3 km altitude in the Tropics down to 0.5%–1% above about 7 km altitude. These values are similar to those observed for GPS/MET for

about the same time of the year [*Poli et al.*, 2002]. The BP standard deviations shown in Figure 1e show a similar pattern to GO, with small improvements in the Tropics above 2 km altitude (difference about 0.5%), and a degradation from 3.5% to 4.5% at 1 km altitude in the same region. The CT standard deviations in Figure 1f show even further reduction as compared to BP, but in the same region as where bias is increased from near-zero for BP to about 1% for CT.

[17] The results above suggest that BP and CT are more consistent with the DAO analyses than GO, with perhaps a small advantage for CT based on its smaller standard deviation above 2 km altitude in the tropics. In an attempt to verify these results, we perform 1DVAR analyses to retrieve temperature from the refractivities, and compare them with close RS. Figure 2a (b) shows bias (standard deviation) of temperature differences fvDAS 6-hour forecasts minus RS, and GO (as well as BP and CT) 1DVAR minus RS.

[18] Any reduction of bias and standard deviation between fvDAS 6-hour forecasts and 1DVAR suggest that GPS RO refractivity have brought in useful information, consistent with the RS which are independent from the fvDAS 6-hour forecasts. Figure 2a shows that GO 1DVAR temperatures are positively biased as compared to RS below 500 hPa, which is due to the global negative refractivity bias at the same altitude as shown by *Poli et al.* [2002]. BP and CT 1DVAR temperatures do not show that bias below the 500 hPa level. Overall, BP and CT 1DVAR temperatures have the smallest biases between -0.2 K and $+0.4$ K, to be compared with -0.6 K and $+0.6$ K for the fvDAS forecasts.

[19] The GO 1DVAR temperatures in Figure 2b show standard deviations of differences with RS reduced by about 0.2 K as compared to the fvDAS 6-hour forecasts around $50-300$ hPa. At $20-50$ hPa all 1DVAR temperatures have standard deviations larger than the fvDAS 6-hour forecasts. In the $10-400$ hPa range, the CT and BP standard deviations are very comparable. Between 300 hPa and 700 hPa, CT has the smallest standard deviation.

[20] The combined comparisons of refractivity with analyses and derived 1DVAR temperatures with RS suggest that BP and CT refractivities are the most consistent and better candidates than GO for data assimilation, with a small advantage for CT.

7. Conclusions and Future Directions

[21] Using data from the CHAMP mission, three processing methods implemented at JPL are compared: geometrical optics, back-propagation, and canonical transform. The latter two methods show closer agreement in refractivity with DAO analyses than the first method. When one-dimensional variational temperature retrievals are performed using the advanced-processed refractivities, a better agreement with close RS is reached with back-propagation and canonical transform data.

[22] Our results indicate that although canonical transform induces refractivity biases larger than back-propagation as compared to DAO analyses, the comparison of their respective temperature retrievals with close RS suggests that those biases may be due to systematic errors in the DAO analyses water vapor fields. Canonical transform appears to be the best choice for generating refractivity data for data assimilation. This opens an opportunity to evaluate the impact of GPS RO data on medium-range weather forecasts and other climate parameters by performing an assimilation over an extended time period.

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